NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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EFFECTS OF FUEL-NOZZLE CARBON DEPOSITION ON COMBUSTION EFFICIENCY OF SINGLE TUBULAR-TYPE, REVERSE-FLOW TURBOJET COMBUSTOR AT SIMULATED ALTITUDE CONDITIONS

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Washington
June 1948

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SUMMARY

An investigation was conducted in order to study the effects of changes in fuel-nozzle carbon deposition on the combustion efficiency of a single tubular-type, reverse-flow, turbojet combustor. This investigation was conducted because of the need to improve the reproducibility of combustion data for fuel-research purposes. The inlet-air conditions simulated operation of a single tubular-type combustor of a turbojet engine in the range of altitudes from 20,000 to 45,000 feet and the range of engine speeds from 10,000 to 15,000 rpm.

At a given combustor-inlet condition, the temperature rise obtained with a clean fuel nozzle was observed to increase after operation of the combustor at other simulated altitude conditions. This increase in temperature rise varied from 565° F at low heat inputs to 30° F at high heat inputs. Removal of the carbon deposit from the fuel nozzle permitted reproduction of the original temperature rise. Shielding the fuel-nozzle body from the combustion zone prevented the deposition of carbon on the nozzle at the conditions investigated and improved the reproducibility of temperature-rise data.

In order to simulate the deposition of carbon, the design of the original fuel nozzle was modified to include a divergent section at the exit of the fuel orifice. This change in fuel-nozzle design increased the combustion efficiency at each operating condition investigated.

INTRODUCTION

In the operation of single tubular-type, reverse-flow, turbojet combustors for fuel-evaluation studies at the NACA Cleveland laboratory, the accurate reproduction of combustion data was difficult. At combustor-inlet-air conditions equivalent to certain altitude operating conditions of the engine, the spread in data between the initial and check runs was at times as great or greater than the change in data produced by an experimental variable. This spread in data was due to an increase in combustor temperature rise; the increase varied with combustor operating time, with operating conditions, and with the composition of the fuel. Although this increase in combustor temperature rise is desirable in service, the uncertainty in research work made it difficult to analyze accurately the experimental data. From previous experience, carbon deposition on the fuel nozzle was suspected to be responsible for the change in combustor temperature rise.

Accordingly, two projects were undertaken: (1) improvement of the reproducibility of temperature-rise data by preventing the deposition of carbon on the fuel nozzle (for this purpose, the combustor was modified by the installation of a shield over the fuel nozzle); (2) improvement of combustion efficiency by modifying the fuel nozzle in order to include a simulated carbon deposition. Combustion data from a single tubular-type combustor operating at several simulated-altitude engine conditions with and without the fuel-nozzle shield and with and without the modified fuel nozzle are presented.

APPARATUS

Combustor and instrumentation. - A single tubular-type, reverse-flow combustor and service fuel nozzles of a turbojet engine were used for this investigation. The service fuel nozzles were rated as 21.5-gallon-per-hour, hollow-cone, 80°-spray-angle nozzles.

The laboratory combustion-air and exhaust facilities were regulated by appropriate equipment in order to obtain the desired combustor inlet-air conditions. The air mass flow was measured by a thin-plate orifice. The temperature and total pressure of the combustor-inlet air were measured by an iron-constantan thermocouple and a total-pressure rake, respectively. The temperature of the combustor-outlet gases was measured by the nine chromel-alumel thermocouples that were located in the combustor-outlet elbow at a position approximately equivalent to the turbine inlet of the engine. A sketch of the combustor, the inlet and outlet ducting, and the instrumentation is shown in figure 1.

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A calibrated rotameter was used to determine the flow of the AN-F-32 fuel used in this investigation.

Fuel-nozzle shield. - The construction and adaptation of the fuel-nozzle shield to the combustor dome is shown in figure 2. Sheet Inconel was formed in a concave shape and trimmed to the dimensions shown. After welding this concave shield to the fuel-nozzle sheath of the combustor dome, a small hole was located on the center line. This hole was gradually enlarged, using a 1/2-inch by 100° countersink until by trial the fuel spray just cleared the shield at the maximum fuel flow expected.

With this device, the air entering the combustor through the annulus surrounding the fuel-nozzle adapter follows the contour of the fuel-nozzle body and emerges alongside the fuel-spray cone. The fuel-air mixture is thus prevented from contacting the fuel nozzle.

Modified fuel nozzle. - From a study of the various carbon formations on fuel nozzles, those deposits that were in a position to be contacted by the fuel-spray cone were found to be effective in increasing the combustor temperature rise. In order to simulate the shape of the carbon deposit, the design of the fuel nozzle was modified to include a divergent section at the exit of the fuel orifice. Although several designs of divergent sections were studied, the optimum design for any specific installation has not been determined. The details of this divergent section, as used in this investigation, are shown in figure 3. A block of solder was attached to a fuel nozzle and machined to the dimensions shown.

The nozzle was assembled in the dome to prevent passage of air through the annulus surrounding the fuel nozzle.

PROCEDURE

Operation. - The combustor operating conditions simulated engine operation at altitude and were selected to provide a variety of inlet-air flows and inlet-air temperatures and pressures. The specific operating conditions are listed in the following table:

Condition	Simulated operation		Combustor-inlet air		
	Altitude (ft)	Engine speed (rpm)	Mass flow (lb/sec)	Pressure (in. Hg abs.)	Temperature ($^{\circ}$F)
1	45,000	10,000	0.361	9.5	30
2	45,000	12,200	.457	12.3	90
3	30,000	13,000	.928	26.0	103
4	30,000	15,000	1.190	35.0	150
5	20,000	14,500	1.550	46.5	175

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The sequence of the operating conditions for the reproducibility investigation without the fuel-nozzle shield was as follows:

Series	Run	Operating condition	Figure	Nozzle
1	1	2	4(a)	Clean
	2	3	4(b)	Untouched
	3	4	4(c)	Untouched
	4	2	4(a)	Untouched
	5	2	4(a)	Untouched
2	6	5	4(d)	Clean
	7	4	4(c)	Untouched
	8	3	4(b)	Untouched
	9	2	4(a)	Untouched
	10	2	4(a)	Cleaned before run

The sequence of the operating conditions for the reproducibility investigation with the fuel-nozzle shield was as follows:

Series	Run	Operating condition	Figure	Nozzle
3	11	2	5(a)	Clean
	12	3	5(b)	Untouched
	13	4	5(c)	Untouched
	14	5	5(d)	Untouched
	15	3	5(b)	Untouched
	16	2	5(a)	Untouched

A modified and an original fuel nozzle were run at conditions 1, 2, 3, and 5 for the combustion-efficiency investigation.

The operation of the combustor consisted in maintaining the desired inlet-air conditions constant and in varying the fuel flow in order to give a series of points above minimum-lean-mixture stable operation or 400° F combustor-outlet temperature, which was the lower limit of the temperature-measuring potentiometer. The fuel flow and temperature measurements were recorded for each point. The combustor assembly was undisturbed during any series of runs.

Calculations. - The combustor temperature rise was computed as the difference between the inlet-air temperature and the arithmetic average of the nine observed temperatures at the combustor-outlet elbow. Although the arithmetic average of the observed temperatures may differ from the true temperature, no correction factors were applied inasmuch as relative values were considered satisfactory for this investigation.

Heat input in Btu per pound of air is the product of fuel-air ratio and the lower heating value of the fuel. The lower heating value of the AN-F-32 fuel used was 18,550 Btu per pound.

Combustion efficiency is defined as

$$\eta_b = \frac{\text{actual enthalpy rise over combustor}}{\text{heating value of fuel supplied}}$$

The necessary values for the computation of the theoretical combustion efficiencies of 40, 60, 80, and 100 percent for each operating condition were obtained from reference 1.

RESULTS AND DISCUSSION

Reproducibility investigation. - The experimental results obtained for the two series of runs without the nozzle shield are shown in figure 4 in which average combustor temperature rise is plotted against heat input. As shown in the preceding table of operating conditions for the reproducibility investigation without the fuel-nozzle shield, the two series of runs differ in the sequence in which the conditions were run. Runs from both series at condition 2 are shown in figure 4(a). Run 1, which was the initial run of the first series, was started with a clean fuel

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nozzle. The variables, which produced curves differing from run 1, were the operating condition and time of the intervening or preceding runs. Runs 1 to 4 were made on the same day and runs 5 to 10 were made at a later date. The curve for run 9, which is in the second series of runs, shows a considerable deviation from the curve of run 1 over most of the range investigated. After removal of the carbon deposit from the fuel nozzle, run 10 practically duplicated run 1. The magnitude of the change in temperature rise, which is attributed to fuel-nozzle carbon deposition, varied over the range of heat inputs investigated. By comparing run 9 with run 10 at a heat input of 340 Btu per pound of air, the change in temperature rise was 565° F (46-percent combustion efficiency); at a heat input of 480 Btu per pound air, the change was 30° F (2-percent combustion efficiency).

Different results were obtained for the two runs at each of conditions 3 and 4 as shown by figures 4(b) and 4(c), respectively. These figures further illustrate the effect that a change in preceding runs and operating time had upon the temperature rise. The curves for the runs of one of the series are not consistently higher than the curves for the runs of the other series as shown by figures 4(a) to 4(c).

The run shown in figure 4(d) was started with a clean fuel nozzle. This figure shows that at operating condition 5 the check points gave a higher temperature rise than the initial points. This increase in temperature rise is attributed to the increasing deposition of carbon on the fuel nozzle during the run. Of the four operating conditions used, temperature rise is most sensitive to fuel-nozzle carbon deposition at condition 2 and condition 5 is most conducive for depositing carbon on the fuel nozzle.

The results of a series of runs made with the fuel-nozzle shield are shown in figure 5. This series of runs was made at the same operating conditions as those used for the unshielded fuel-nozzle series. Run 11 (fig. 5(a)) was started with a clean fuel nozzle and during the succeeding runs of this series the nozzle was untouched. The data of run 16 (fig. 5(a)), which was the last run of this series, are in good agreement with the data of the initial run 11. The intervening runs at conditions 3, 4, and 5 apparently had little or no effect on combustor performance. Good reproducibility is also shown in figure 5(b) for two runs with the fuel-nozzle shield at condition 3. These runs were made on different days with intervening runs at conditions 4 and 5. The results of run 13 at condition 4 are shown in figure 5(c) as a part of this series of runs for which the combustor was operating for 61 minutes. The data obtained at condition 5 are plotted in figure 5(d). In contrast with the data of figure 4(d), the check points here fall on the initial curve. At the completion of the series of runs with the fuel-nozzle shield, no carbon deposit was found on the fuel nozzle although some carbon deposited on the face of the fuel-nozzle shield.

At operating condition 2, the temperature rise obtained with a shielded fuel nozzle was approximately 20 percent lower at low heat inputs and was approximately equal at high heat inputs to that obtained with a clean unshielded fuel nozzle. (Compare run 1, fig. 4(a) with run 11, fig. 5(a).) At condition 5, the temperature rise obtained with a shielded fuel nozzle was approximately equal to that obtained with a clean unshielded fuel nozzle for most of the heat-input range investigated. (Compare run 6, fig. 4(d) with run 14, fig. 5(d).)

Although the reproducibility of data for each shielded fuel-nozzle installation was good, a small variation in data occurred for different fuel nozzles or combustor assemblies during preliminary trials.

Combustor-efficiency investigation. - In figures 6(a) to 6(d), combustor-temperature-rise values for the modified fuel nozzle are compared with data from the original nozzle at operating conditions 1, 2, 3, and 5, respectively. These figures show that for a given heat input the combustion efficiency obtained with the modified fuel nozzle was higher throughout the range of heat inputs investigated than the combustion efficiency obtained with the original fuel nozzle at each of the four operating conditions. At each operating condition, the combustion efficiency for the modified fuel nozzle was practically constant over the range of heat inputs investigated; whereas, the combustion efficiency for the original fuel nozzle varied with the heat input or fuel flow.

The minimum fuel flow for the original fuel nozzle at which combustion could be maintained was 34 pounds per hour with an efficiency of approximately 60 percent (fig. 6(a)). In contrast, the modified fuel nozzle maintained combustion at a fuel flow of 16 pounds per hour with an efficiency of 80 percent. Similar results are shown for the other three operating conditions in figures 6(b) to 6(d). A study of these results suggests that the operational range of the engine at the altitudes investigated could be extended in the low fuel-flow and air-flow region by the use of the modified nozzle.

The increase in combustion efficiency, which the check points of both nozzle runs show in figure 6(a), may be due to the deposition of carbon during the run.

A composite of fuel-spray photographs of the modified and original fuel nozzles at fuel flows in the range of 11.2 to 83.0 pounds per hour is shown in figure 7. Although these fuel sprays were conducted in a quiescent atmosphere, they serve to indicate the differences in fuel-spray configuration for the two types of fuel nozzle. As the fuel flow rate through the original fuel nozzle was decreased from 83 pounds per hour, the included angle of the fuel-spray cone decreased until a small bulb was formed at a flow of 24.9 pounds per hour (fig. 7(a)). In contrast, figure 7(b) shows that as the fuel flow through the modified nozzle was decreased from 83 pounds per hour, the included angle of the fuel-spray cone increased and attained a maximum value of 180° at a flow of approximately 20.3 pounds per hour.

Relating the fuel-spray configurations for the original fuel nozzle as shown in figure 7(a) with the combustion efficiencies at various fuel flows as shown in figures 6(a) to 6(d), would indicate that the combustion efficiency decreased as the included angle of the fuel-spray cone decreased, and that combustion ceased at fuel flows that produce the bulb-type fuel spray. A similar comparison for the modified fuel nozzle suggests that the high combustion efficiencies obtained with this nozzle at low fuel flows may be due to the large angle of the fuel-spray cone maintaining normal distribution of fuel in the proximity of the fuel nozzle.

No attempt was made to determine the reproducibility of results at this stage of the fuel-nozzle development.

SUMMARY OF RESULTS

The following results were obtained on a single tubular-type, reverse-flow, turbojet combustor operating at inlet-air conditions corresponding to an engine operating in the range of altitudes from 20,000 to 45,000 feet and in the range of engine speeds from 10,000 to 15,000 rpm.

Reproducibility Investigation

1. At an inlet-air condition simulating an altitude of 45,000 feet and an engine speed of 12,200 rpm at a given fuel

input the combustor-outlet temperature obtained after the fuel nozzle accumulated a deposit of carbon was higher than that obtained with a clean fuel nozzle. This increase in temperature varied from 565° F (46-percent combustion efficiency) at low heat inputs (fuel flows) to 30° F (2-percent combustion efficiency) at high heat inputs. Removal of the carbon deposit from the fuel nozzle permitted reproduction of the original clean-fuel-nozzle combustor-outlet temperature.

2. Shielding the fuel-nozzle body from the combustion zone prevented the deposition of carbon on the fuel nozzle at the conditions investigated and improved the reproducibility of combustor-outlet temperature data.

3. The temperature rise (from inlet to outlet of the combustion chamber) obtained with a shielded fuel nozzle was approximately 20 percent lower at low heat inputs and was approximately equal at high heat inputs to that obtained with a clean unshielded nozzle.

Efficiency Investigation

1. In order to simulate the deposition of carbon, the design of the original fuel nozzle was modified to include a divergent section at the exit of the fuel orifice. The combustion efficiency obtained with the modified fuel nozzle was higher throughout the range of heat inputs investigated than the combustion efficiency obtained with the original fuel nozzle at each of the four operating conditions used.

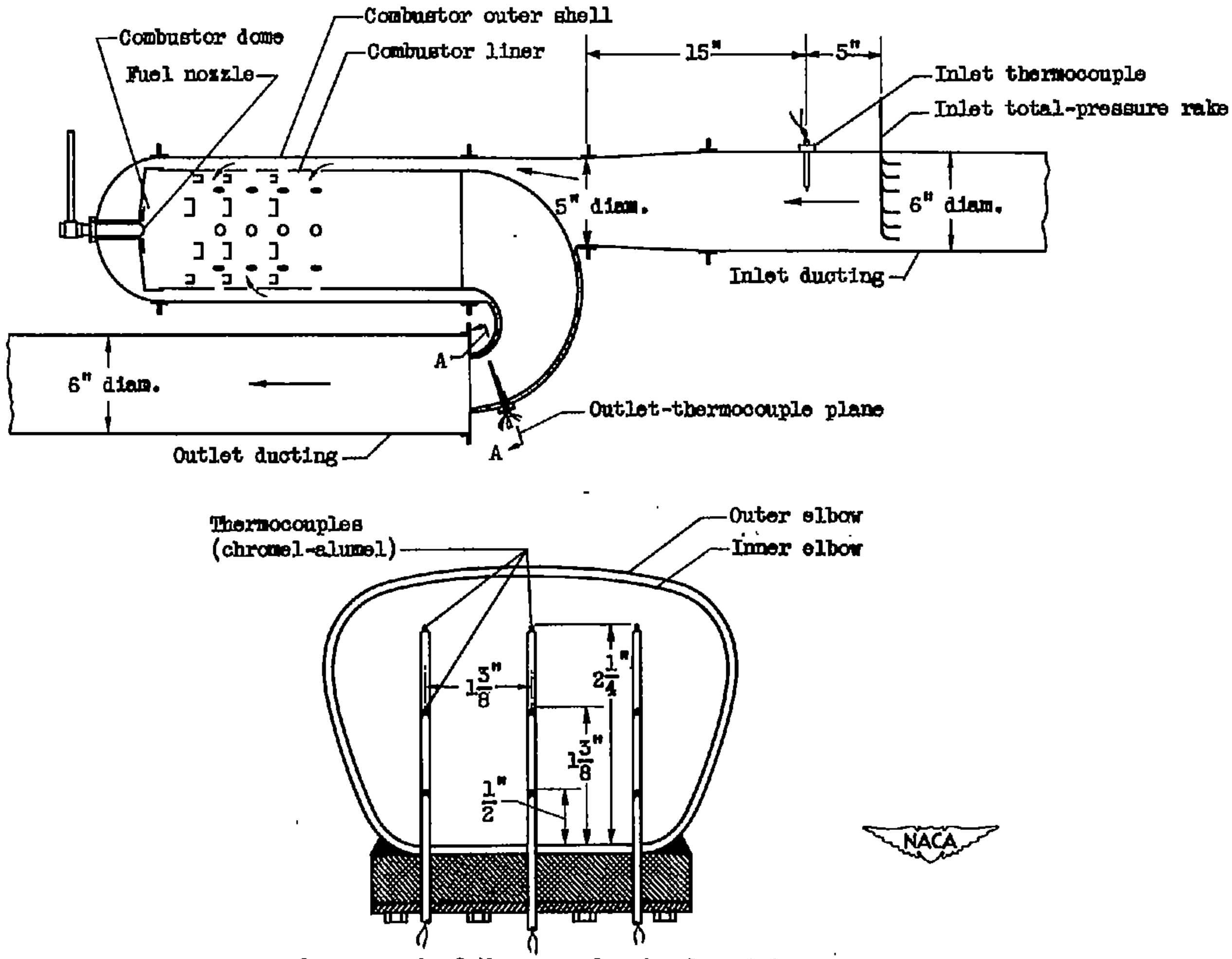
2. At each operating condition, the combustion efficiency for the modified fuel nozzle was practically constant over the range of fuel flows investigated; whereas, the combustion efficiency for the original fuel nozzle varied with the fuel flow.

3. At an inlet-air condition corresponding to an engine operating at an altitude of 45,000 feet and an engine speed of 10,000 rpm, the modified fuel nozzle maintained combustion with an efficiency of 80 percent at a fuel flow of 16 pounds per hour. In contrast, the minimum fuel flow at which the original fuel nozzle maintained combustion was 34 pounds per hour with an efficiency of approximately 60 percent.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 10, 1948.

REFERENCE

1. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN No. 1086, 1946.



Arrangement of thermocouples in plane A-A

Figure 1. - Diagrammatic sketch of single tubular-type reverse-flow combustor showing ducting and instrumentation.

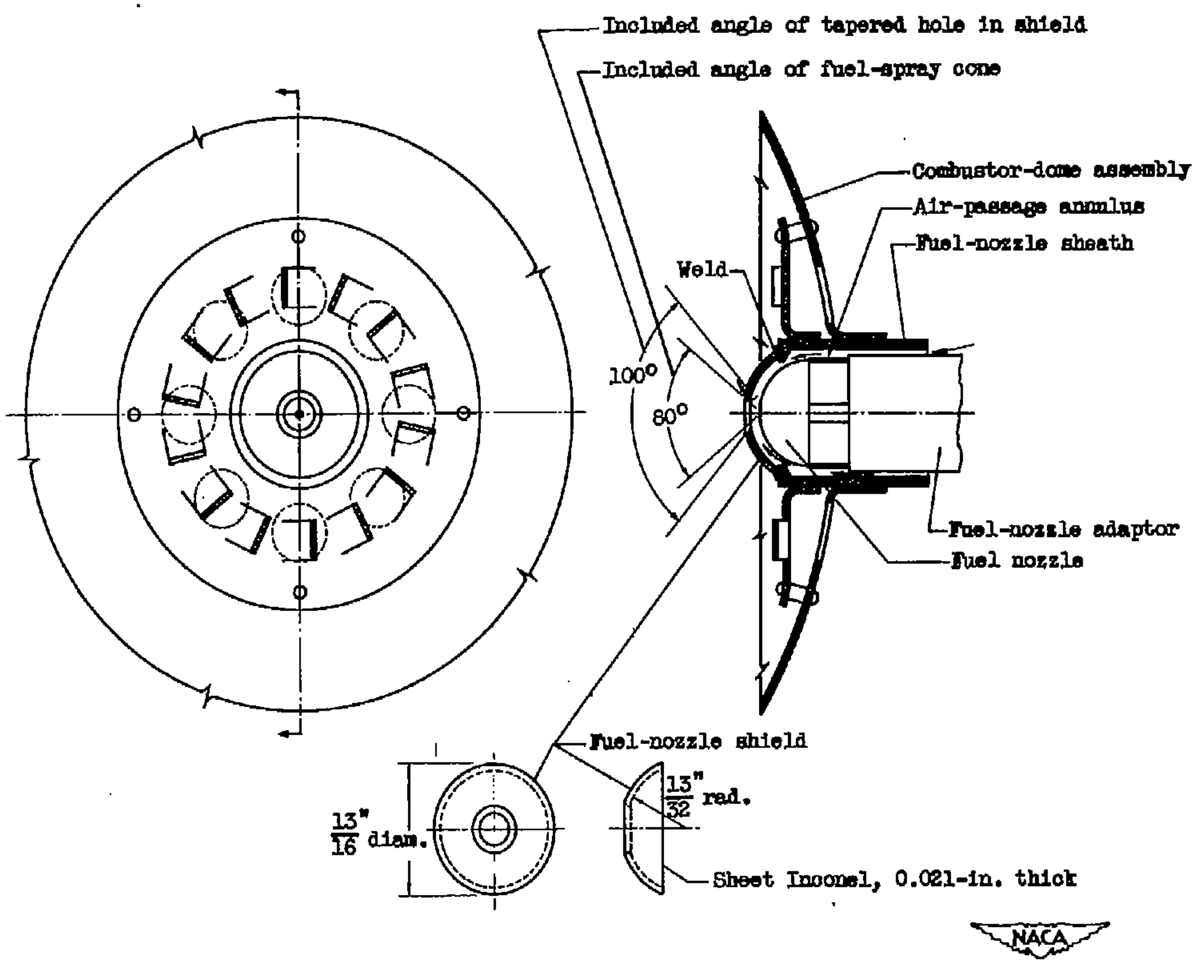


Figure 2. - Details of construction and adaptation of fuel-nozzle shield to combustor-dome assembly.

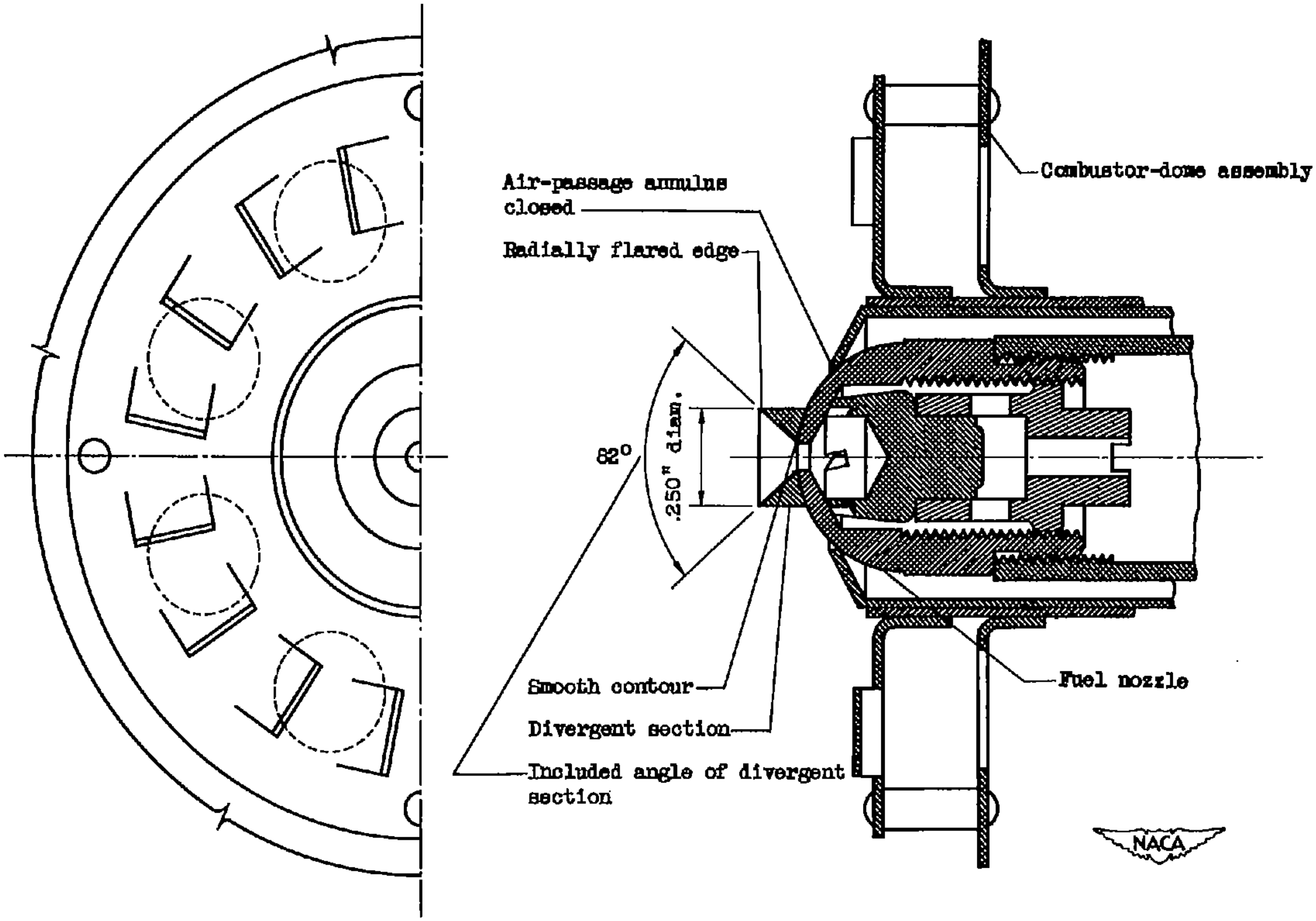
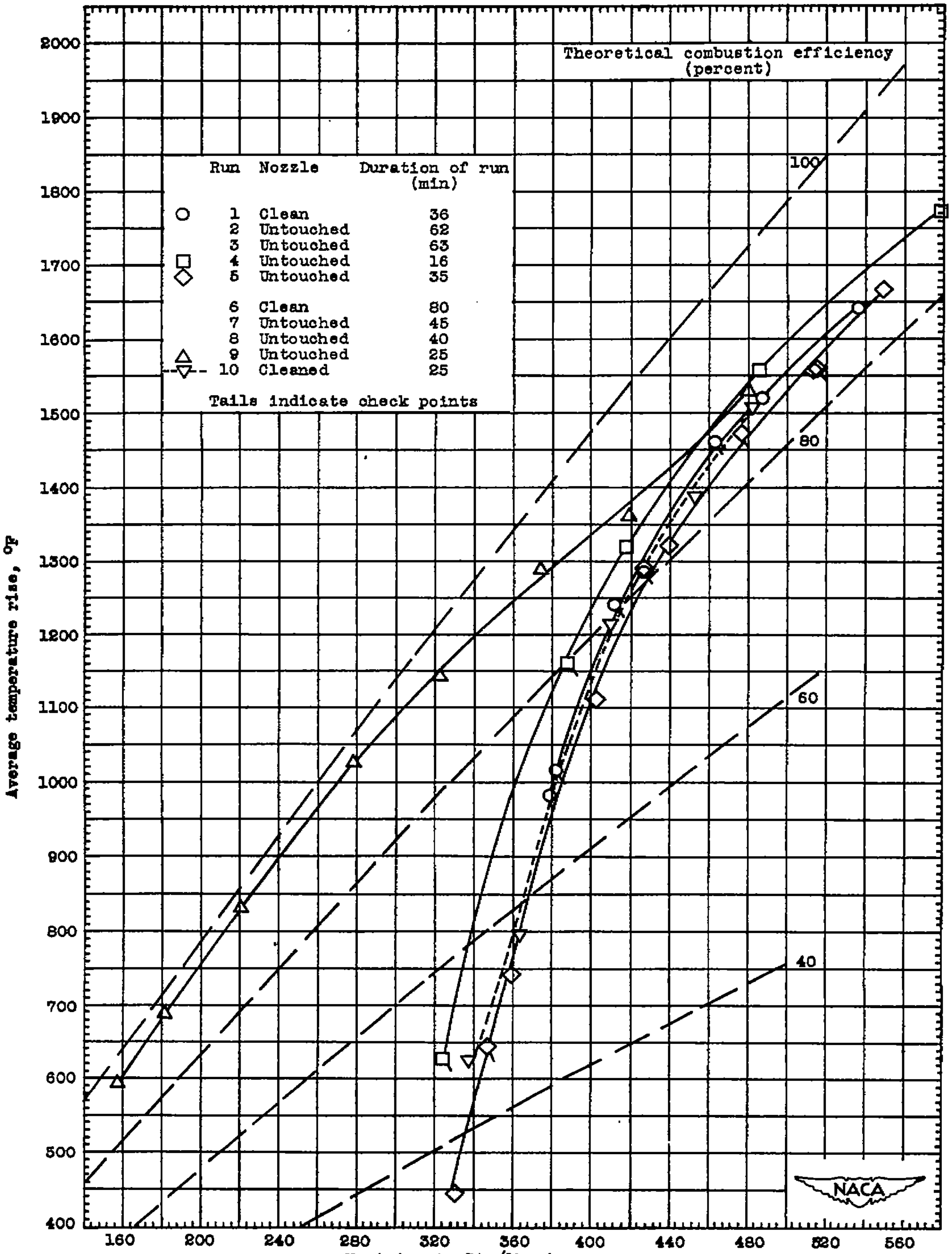


Figure 3. - Diagrammatic sketch of modified fuel nozzle showing details of divergent section at exit of fuel nozzle.



(a) Simulated altitude, 45,000 feet; simulated engine speed, 12,200 rpm; inlet-air weight flow, 0.457 pound per second; inlet-air pressure, 12.3 inches mercury absolute; inlet-air temperature, 90° F.

Figure 4. - Variation of temperature rise with heat input in single tubular-type turbojet combustor without fuel-nozzle shield.

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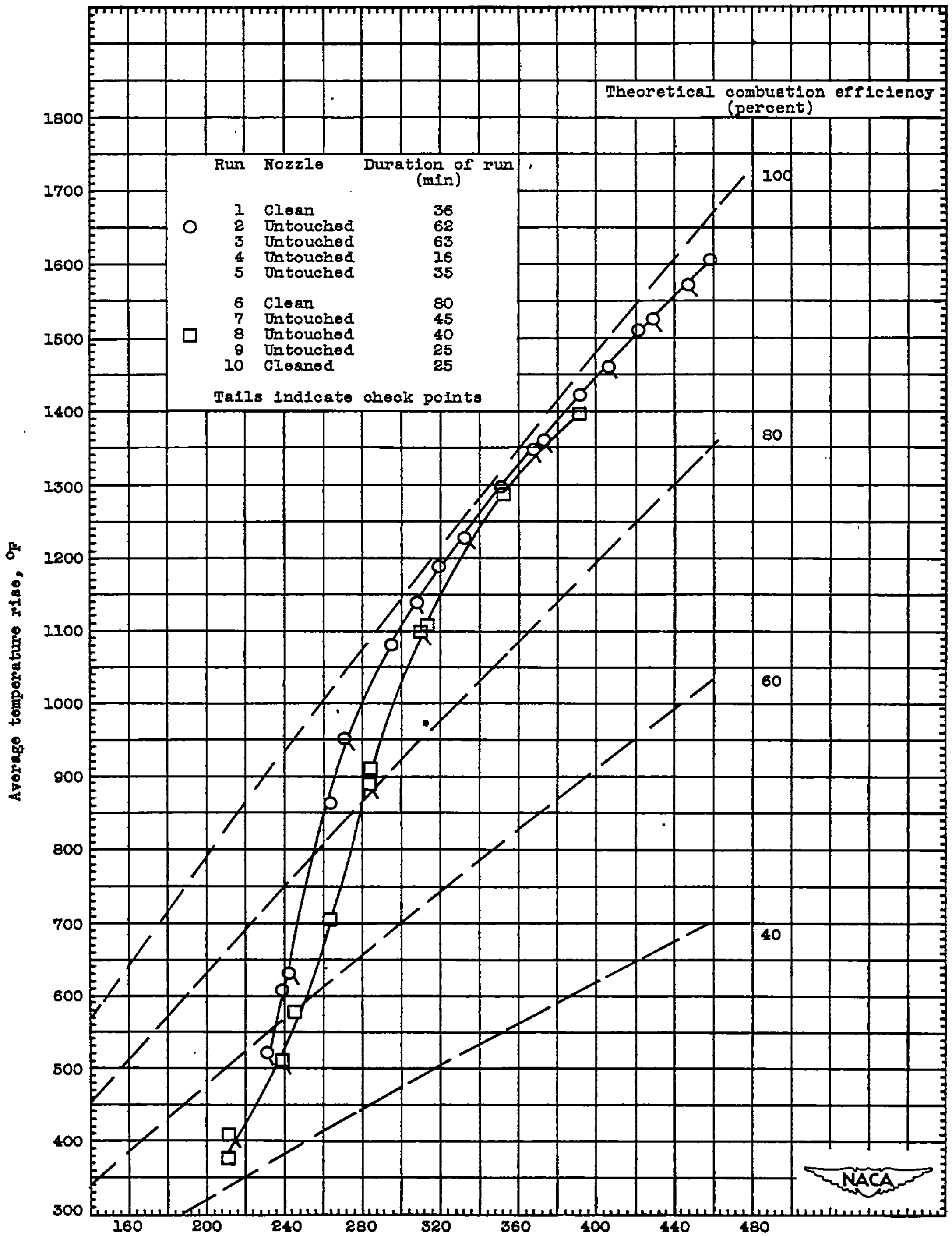
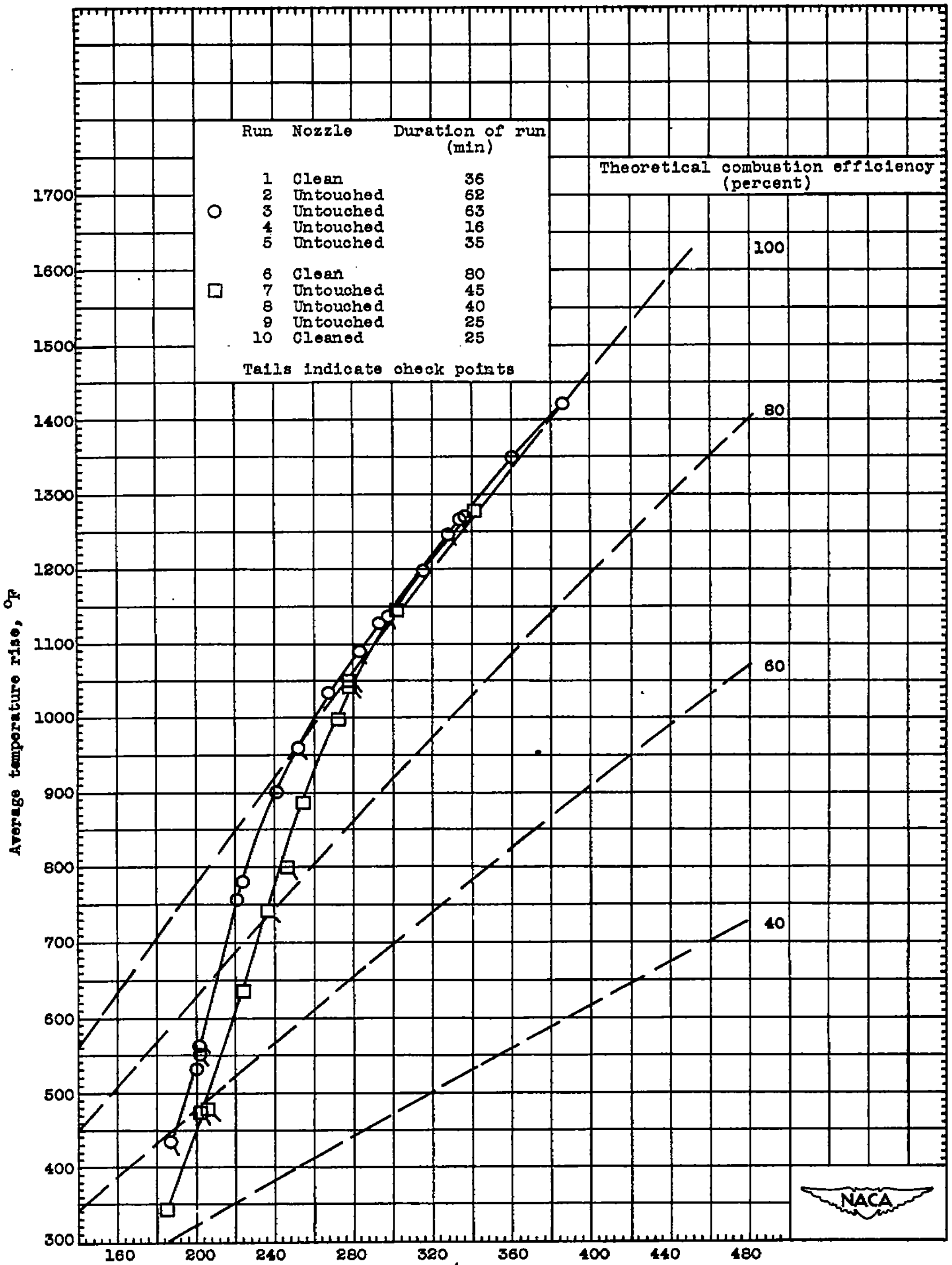


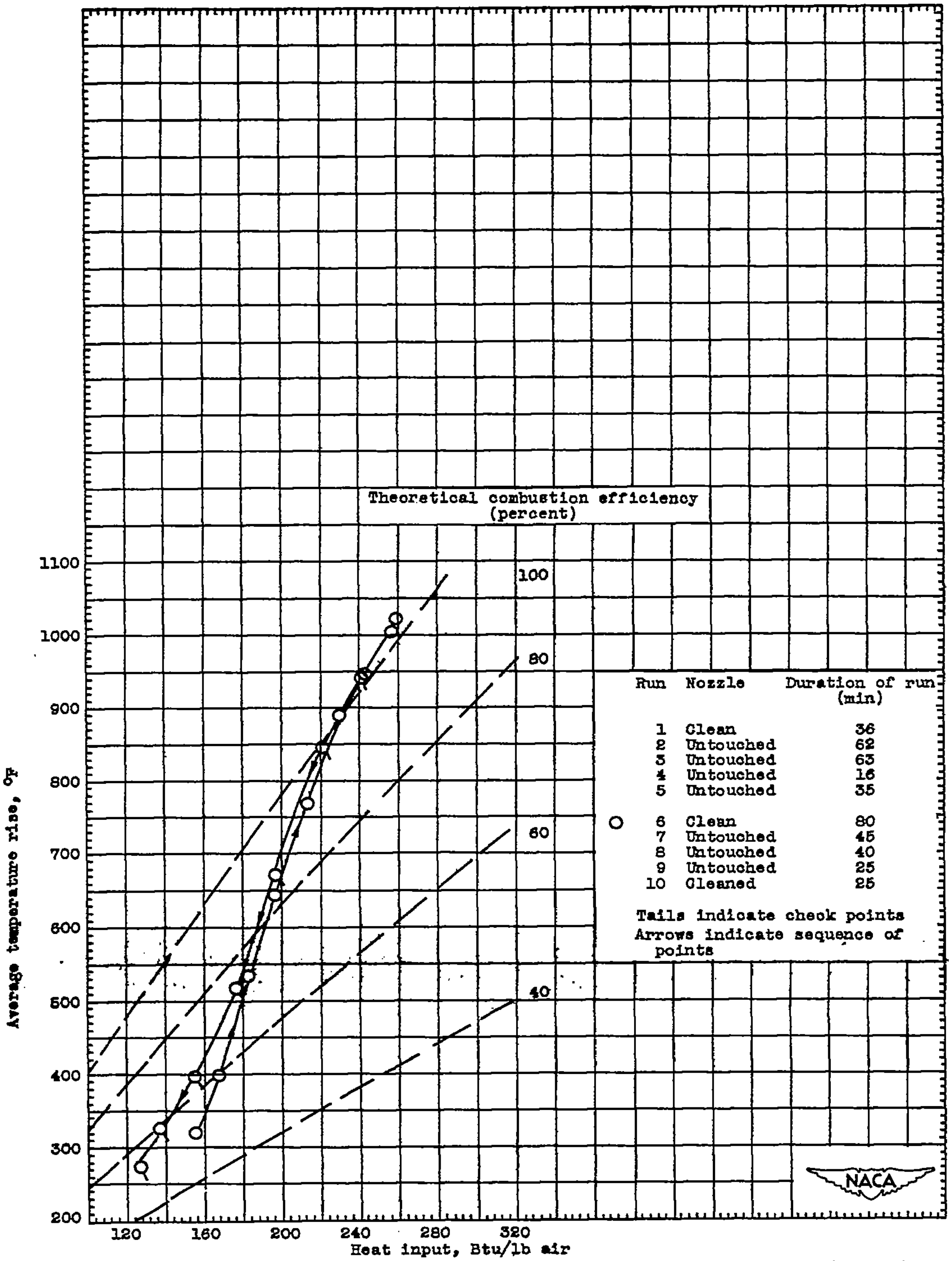
(b) Simulated altitude, 30,000 feet; simulated engine speed, 13,000 rpm; inlet-air weight flow, 0.928 pound per second; inlet-air pressure, 26.0 inches mercury absolute; inlet-air temperature, 103° F.

Figure 4. - Continued. Variation of temperature rise with heat input in single tubular-type turbojet combustor without fuel-nozzle shield.



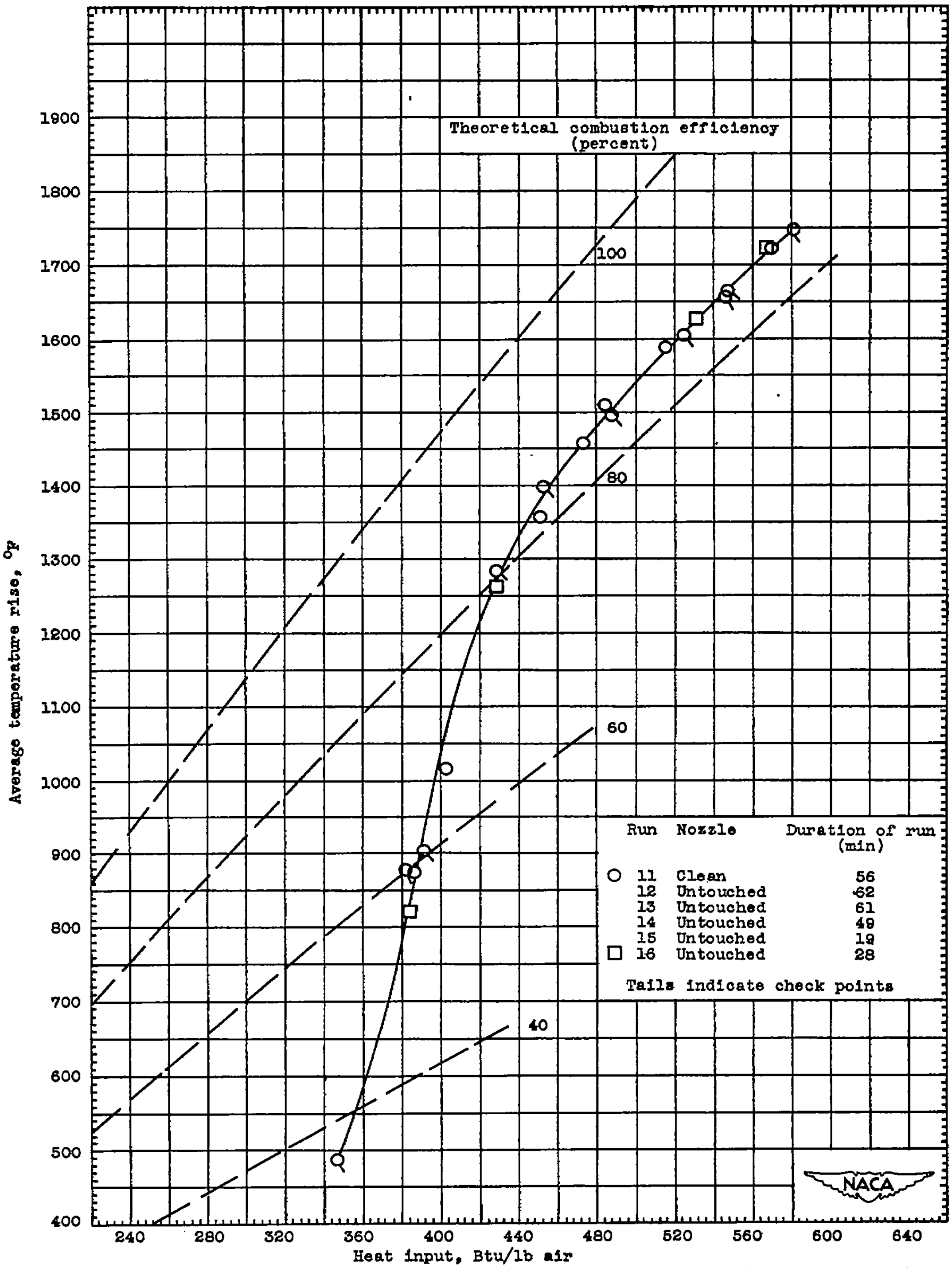
(c) Simulated altitude, 30,000 feet; simulated engine speed, 15,000 rpm; inlet-air weight flow, 1.19 pounds per second; inlet-air pressure, 35.0 inches mercury absolute; inlet-air temperature, 150° F.

Figure 4. - Continued. Variation of temperature rise with heat input in single tubular-type turbojet combustor without fuel-nozzle shield.



(d) Simulated altitude, 20,000 feet; simulated engine speed, 14,500 rpm; inlet-air weight flow, 1.55 pounds per second; inlet-air pressure, 46.5 inches mercury absolute; inlet-air temperature, 175° F.

Figure 4. - Concluded. Variation of temperature rise with heat input in single tubular-type turbojet combustor without fuel-nozzle shield.



(a) Simulated altitude, 45,000 feet; simulated engine speed, 12,200 rpm; inlet-air weight flow, 0.457 pound per second; inlet-air pressure, 12.3 inches mercury absolute; inlet-air temperature, 90° F.

Figure 5. - Variation of temperature rise with heat input in single tubular-type turbojet combustor with fuel-nozzle shield.

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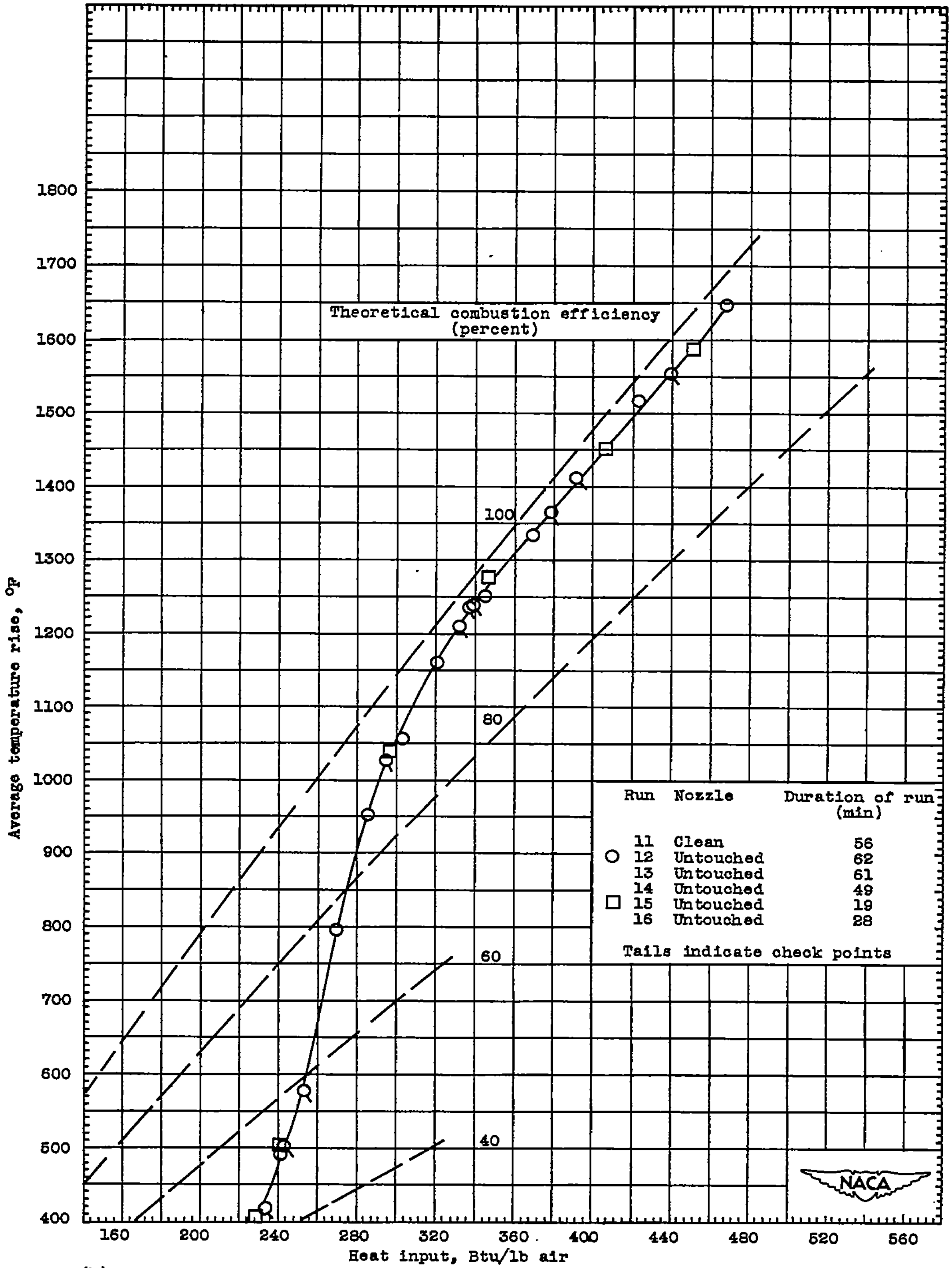
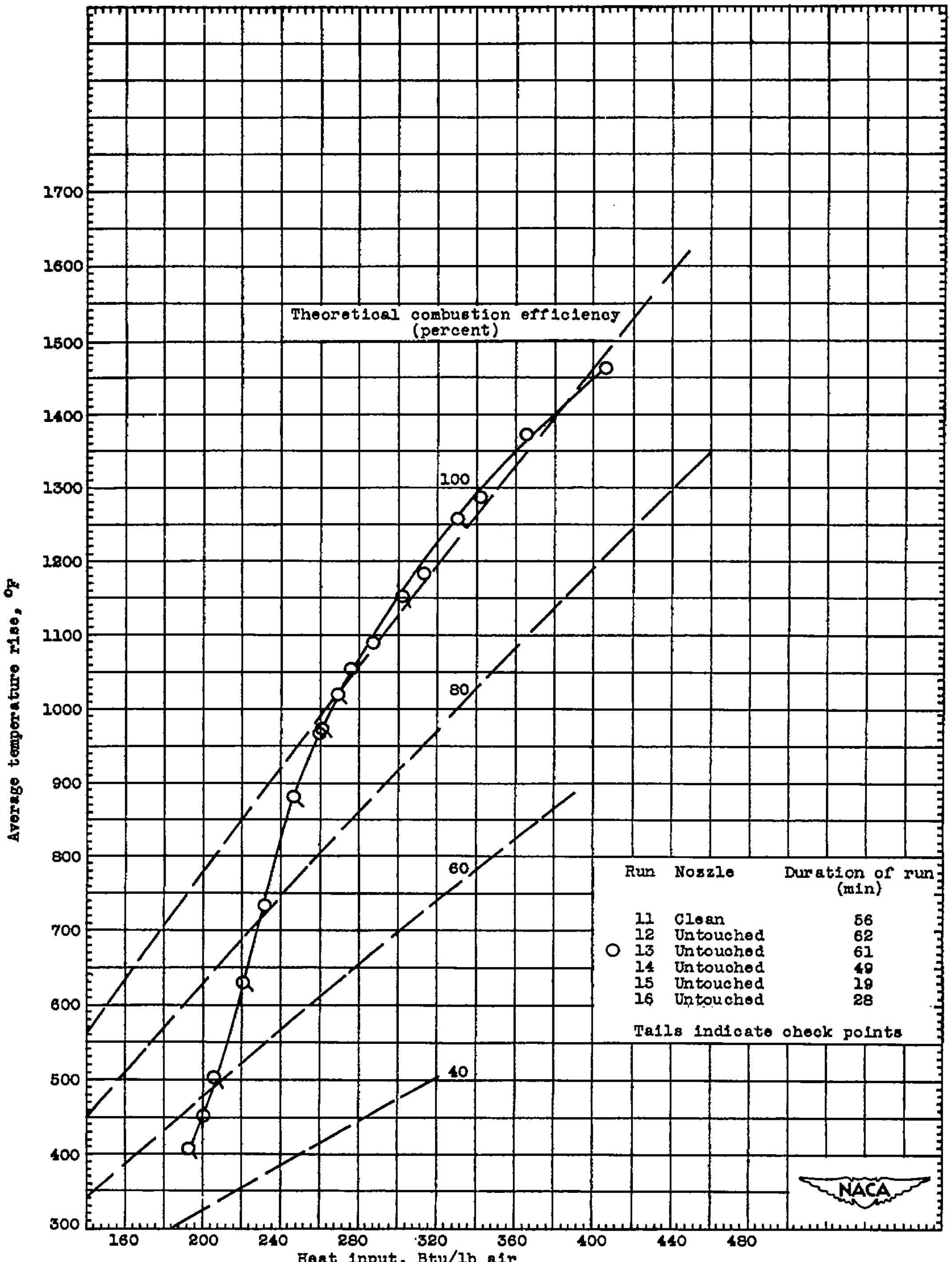


(b) Simulated altitude, 30,000 feet; simulated engine speed, 13,000 rpm; inlet-air weight flow, 0.928 pound per second; inlet-air pressure, 26.0 inches mercury absolute; inlet-air temperature, 103° F.

Figure 5. - Continued. Variation of temperature rise with heat input in single tubular-type turbojet combustor with fuel-nozzle shield.



(c) Simulated altitude, 30,000 feet; simulated engine speed, 15,000 rpm; inlet-air weight flow, 1.19 pounds per second; inlet-air pressure, 35.0 inches mercury absolute; inlet-air temperature, 150° F.

Figure 5. - Continued. Variation of temperature rise with heat input in single tubular-type turbojet combustor with fuel-nozzle shield.

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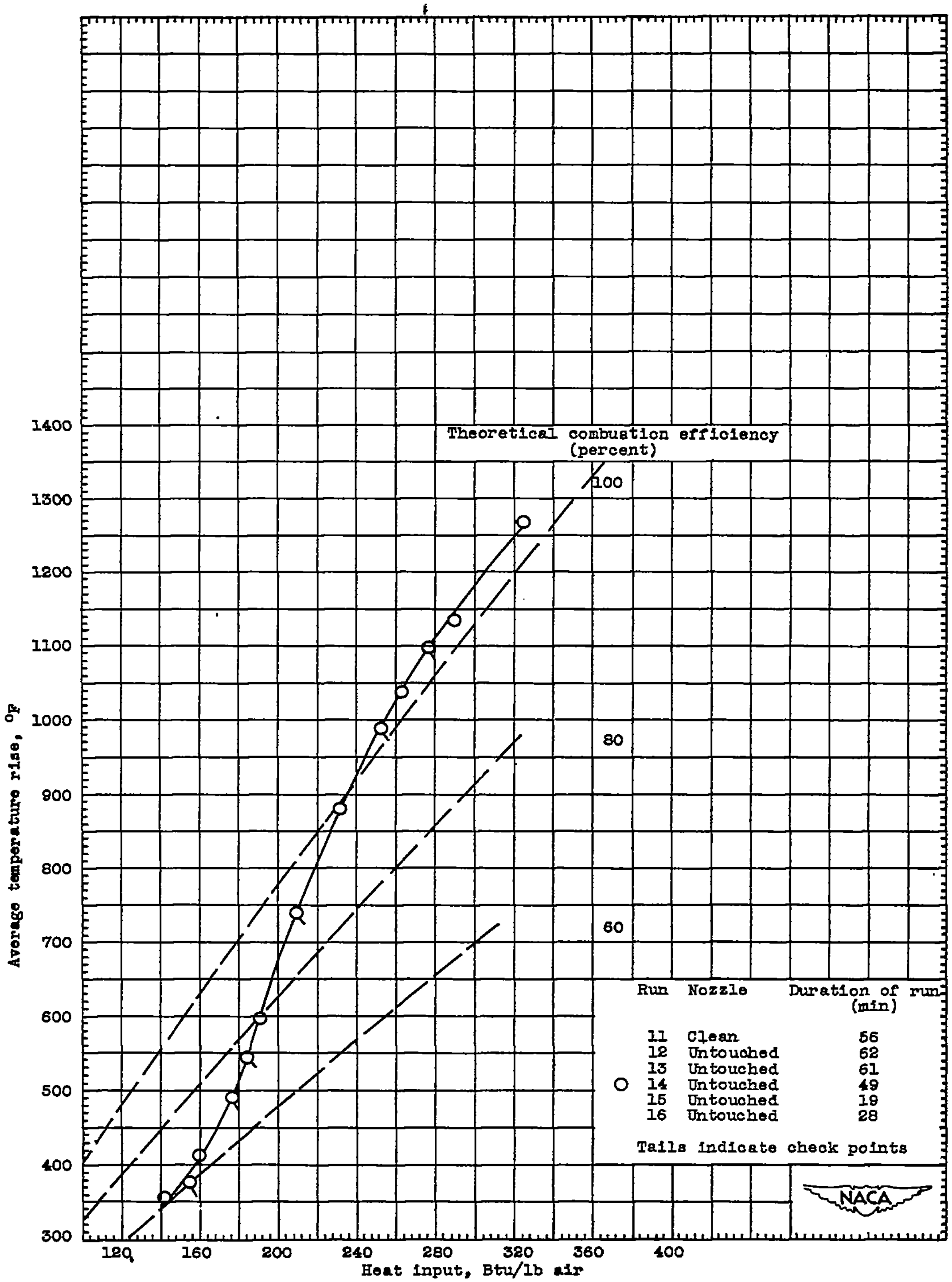
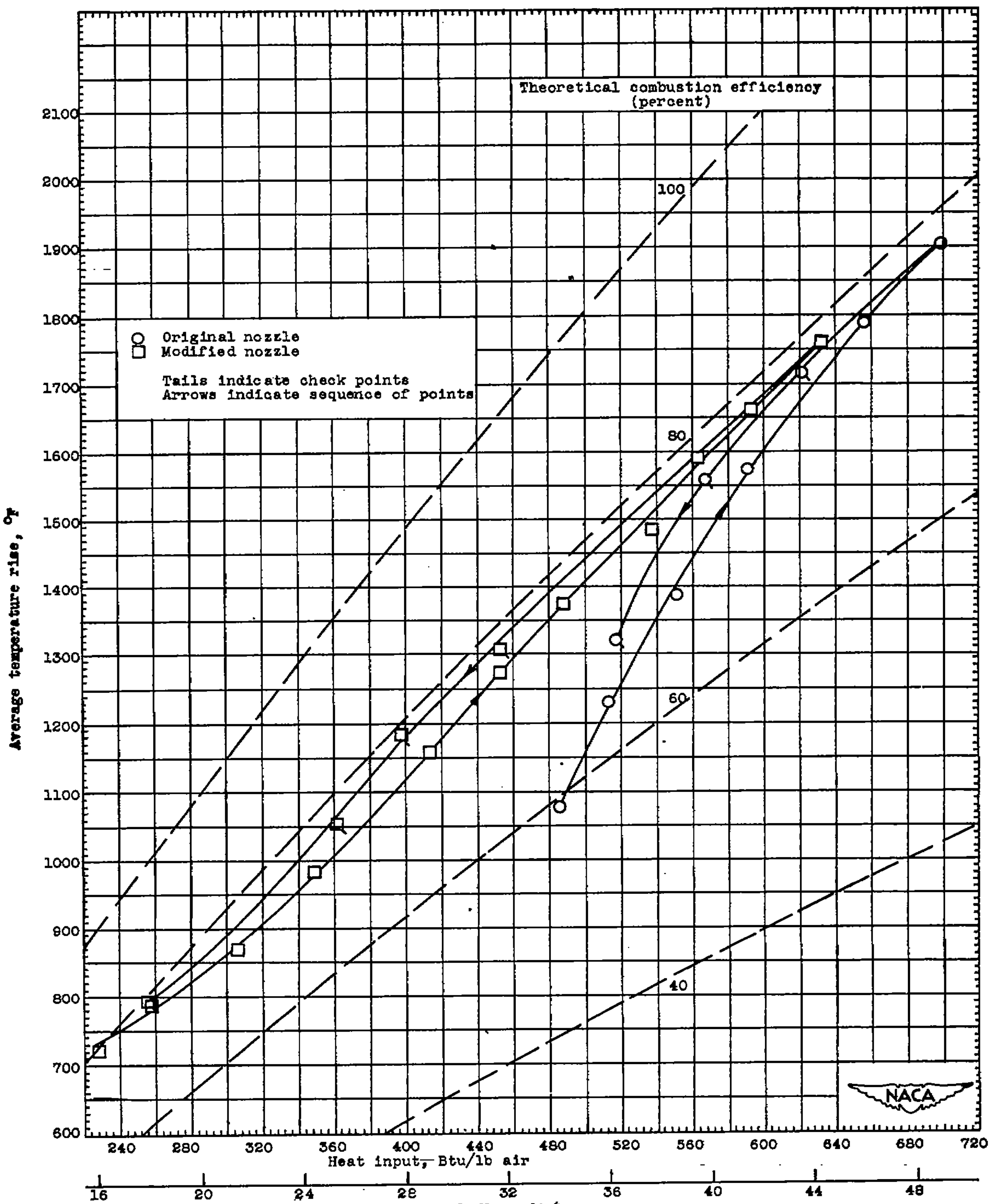


(d) Simulated altitude, 20,000 feet; simulated engine speed, 14,500 rpm; inlet-air weight flow, 1.55 pounds per second; inlet-air pressure, 46.5 inches mercury absolute; inlet-air temperature, 175° F.

Figure 5. - Concluded. Variation of temperature rise with heat input in single tubular-type turbojet combustor with fuel-nozzle shield.



(a) Simulated altitude, 45,000 feet; simulated engine speed, 10,000 rpm; inlet-air weight flow, 0.361 pound per second; inlet-air pressure, 9.5 inches mercury absolute; inlet-air temperature, 30° F.

Figure 6. - Effect of fuel-nozzle modification on temperature rise obtained for various heat-input values in single tubular-type turbojet combustor.

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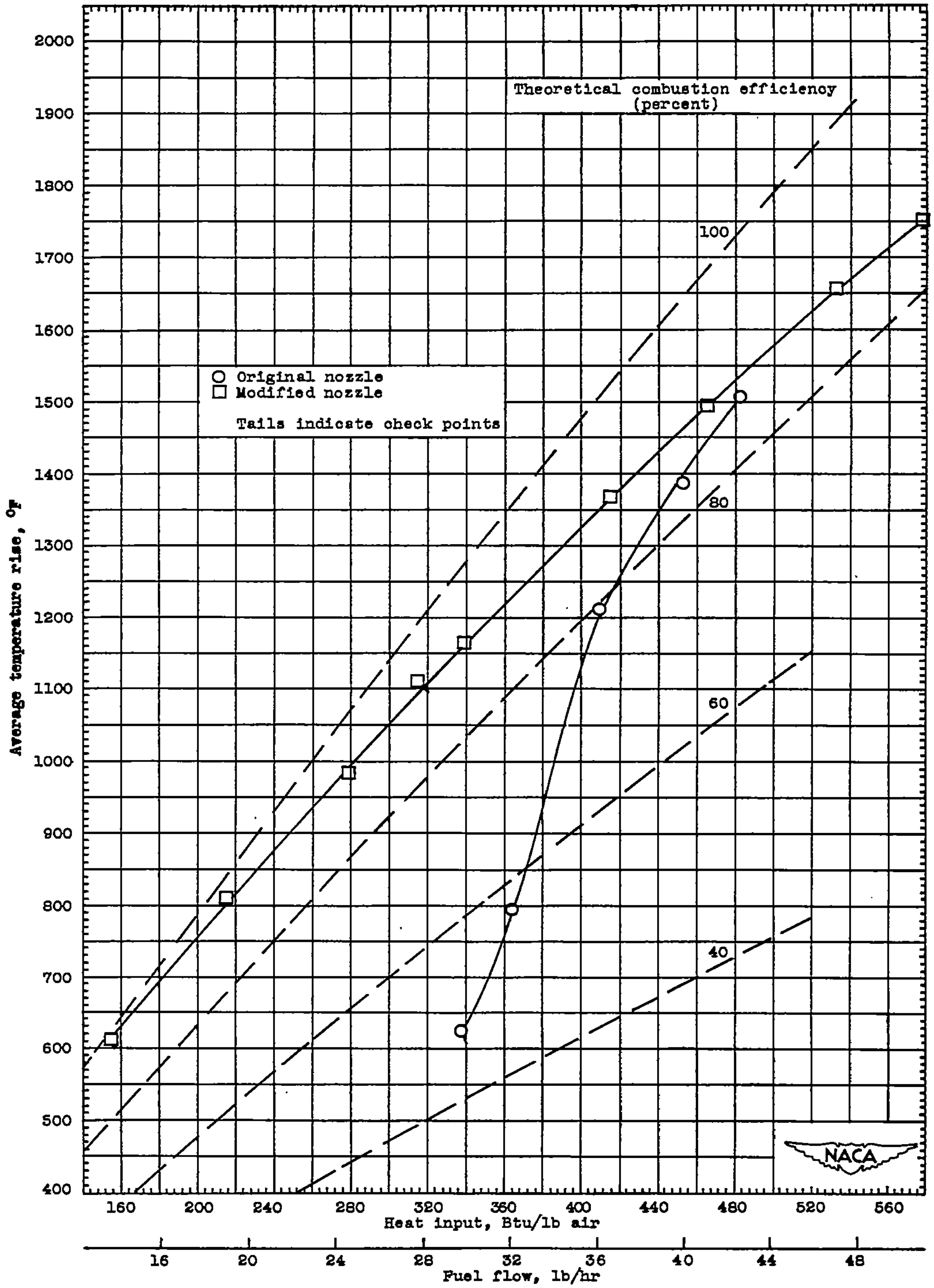
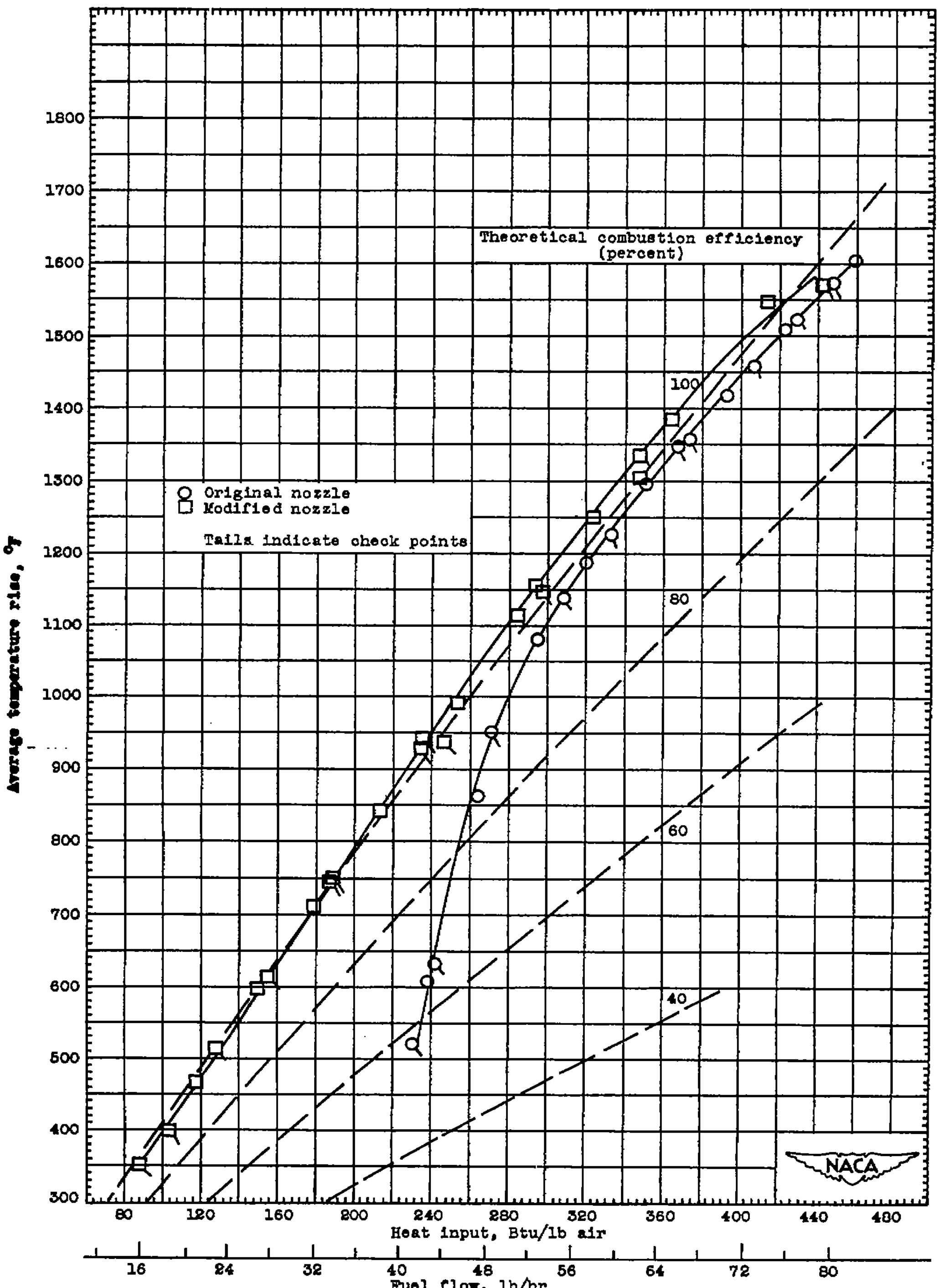


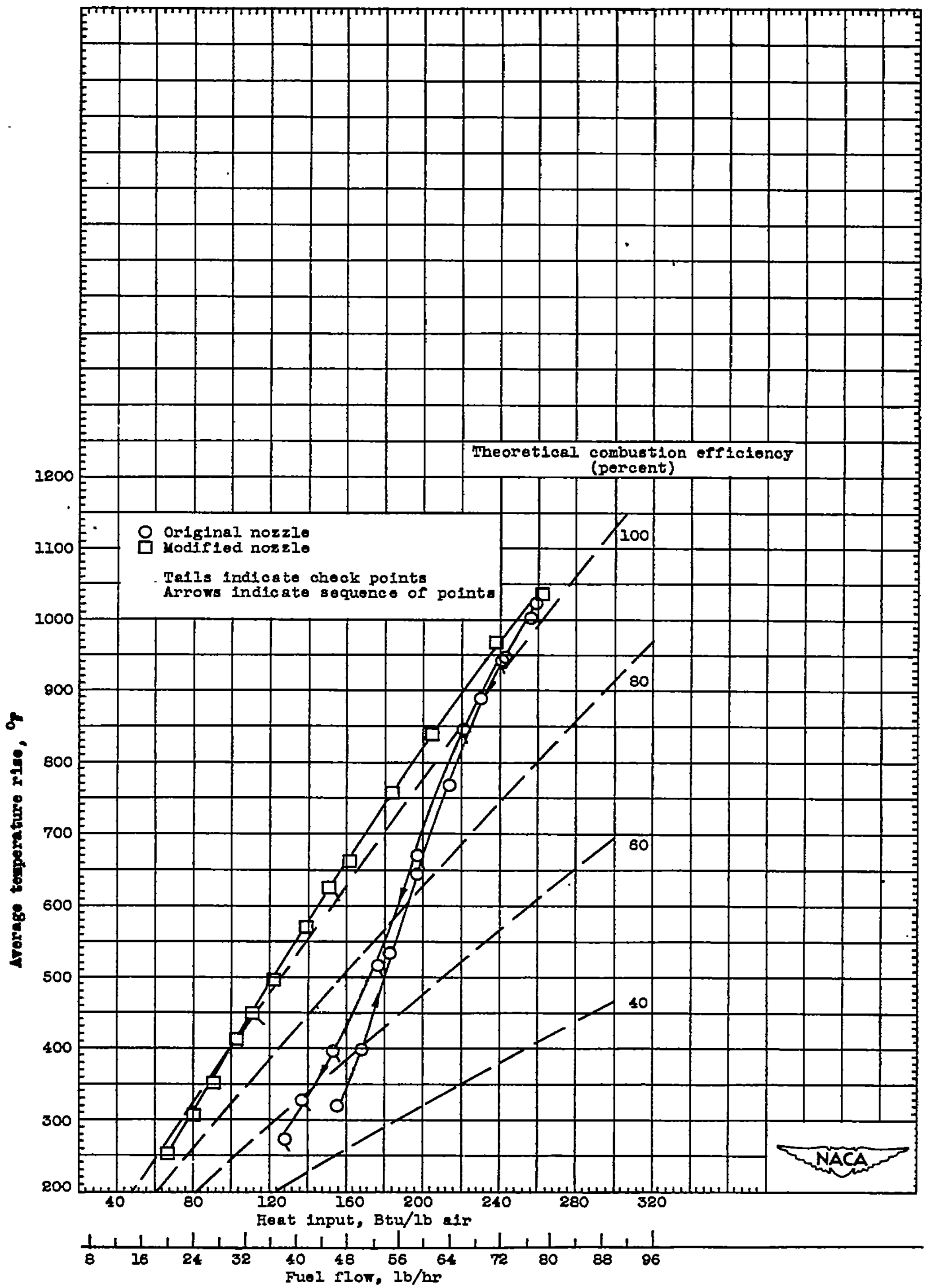
(b) Simulated altitude, 45,000 feet; simulated engine speed, 12,200 rpm; inlet-air weight flow, 0.457 pound per second; inlet-air pressure, 12.3 inches mercury absolute; inlet-air temperature, 90° F.

Figure 6. - Continued. Effect of fuel-nozzle modification on temperature rise obtained for various heat-input values in single tubular-type turbojet combustor.



(c) Simulated altitude, 30,000 feet; simulated engine speed, 13,000 rpm; inlet-air weight flow, 0.928 pound per second; inlet-air pressure, 26.0 inches mercury absolute; inlet-air temperature, 103° F.

Figure 6. - Continued. Effect of fuel-nozzle modification on temperature rise obtained for various heat-input values in single tubular-type turbojet combustor.



(d) Simulated altitude, 20,000 feet; simulated engine speed, 14,500 rpm; inlet-air weight flow, 1.55 pounds per second; inlet-air pressure; 46.5 inches mercury absolute; inlet-air temperature, 175° F.

Figure 6. - Concluded. Effect of fuel-nozzle modification on temperature rise obtained for various heat-input values in single tubular-type turbojet combustor.

11.2 | 15.9 | 20.2 | 24.9

Fuel flow, lb/hr

0.8 | 1.4 | 2.0 | 2.9

Fuel pressure, lb/sq in. gage

(a)-Original fuel nozzle.

11.3 | 15.2 | 20.3 | 24.9

Fuel flow, lb/hr

1.0 | 1.4 | 2.1 | 3.2

Fuel pressure, lb/sq in. gage

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7.21.47

(b) - Modified fuel nozzle.

Figure 7. - Variation of fuel-spray configuration with fuel flow for two fuel-nozzle designs.

30.4	40.5	83.0

Fuel flow, lb/hr

4.5	7.2	34.0

Fuel pressure, lb/sq in. gage

(a) -Concluded. Original fuel nozzle.

30.0	40.2	83.0

Fuel flow, lb/hr

4.7	8.6	36.5

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Fuel pressure, lb/sq in. gage

(b) -Concluded. Modified fuel nozzle.

Figure 7. - Concluded. - Variation of fuel-spray configuration with fuel flow for two fuel-nozzle designs.